Kinetic geiger dome with photovoltaic panelsstructural membranes 2013

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KINETIC GEIGER DOME WITH PHOTOVOLTAIC PANELS STRUCTURAL MEMBRANES 2013

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Summary. In this paper we describe the kinetic transformation of a Geiger dome in order to create a (large span) roof surface with photovoltaic elements that can be faced to the sun during the day. The purpose of this structure is to combine a sun tracker with an architectural building.

1 INTRODUCTION

For solar cells, such as photovoltaic panels, the angle of incidence between the incoming light and the solar cells determines the efficiency. By placing the cells on trackers the amount of energy produced can be increased significantly compared to fixed arrays of solar cells. Dual-axis tracking systems are relatively expensive and complicated compared to single-axis tracking systems, and have a relatively small benefit.[1] The integration of kinetic sun-tracking systems in building concepts is the challenge of this research. The objective is to create as much energy as possible with limited solar cells on a kinetic roof surface. This research in kinetic domes aims to achieve the same objectives as responsive architecture as described by Tristan d'Estrée Sterk, Geoffrey Thün and Kathy Velikov. In our case the structure is not programmed by computers or responsive in a digital way.[2] [3] [4] We focused on optimizing the harvesting of solar energy (day-night cycle, seasons, different azimuth and altitude) on a kinetic tensegrity dome.

1.1 Research methodology

A large part of the research was done in ateliers with Master students Building Technology (TU Eindhoven). After defining the research question, each student researched literature. They made design proposals from which the most interesting ideas were chosen or combined. Testing of crucial parts was done before the production of a 1:1 prototype. The structural and kinetic behavior and principles of several options were researched, for example the Geigerdome and the so-called "Leonardo dome". Different models of scale 1:20 were made and a sunlight study was done to see the relation between the path of the sun and the deformation of the dome. The students have been in a continuous iterative process [5] of observation, induction, deduction, testing and evaluation (empirical cycle according to A.D. de Groot).[6]

2 SOLAR ENERGY

Most buildings, and their geometries are fairly static which limits the possibilities for adaption of the building surface to optimal energy performance. The research programs CABS and FACET show that different types of skins perform better in different seasons.[7] [8] If we like to achieve optimal behavior during the four seasons, during the day- night cycle and for different inhabitants (users) there is a need for adaptable kinetic skins and/or kinetic geometries.

2.1 Solar cells

We did not research the exact output and price of different systems, we only focused on the output by tracking the sun. An important aspect is the weight, as the objective of this research is to create large spans with a light-weight kinetic geometry. Including the support structure crystalline panels are 3 to 4 times as heavy as solar foils. The crystalline cells have a lifespan of approximately 25-30 years with an efficiency of 15–20%, while the amorphous foils have a lifespan of 15 years with an efficiency of 6–10%. While solar foils have an advantage in weight and form freedom, the output and lifespan is lower. Foils can be integrated in a membrane roof.

2.2 Sun trackers

The orientation of the solar cells is an important factor in its energy efficiency. The best sun-tracker therefore would be one that constantly measures the position of the sun and changes the angles of the solar cells accordingly, so that they are always perpendicular towards the sun.[9] Tracking systems allow solar cells to follow the path of the sun. There are single-axis trackers and dual-axis trackers. With tracked solar cells it is possible to have the same output with less solar cells. This means less weight, less construction and a smaller invertor. The effect of trackers is much higher in the summer. Tracking is feasible one hour after sunrise and one hour before sunset. A misalignment of 10 degrees will reduce the output by only 2%. A bigger misalignment, however, reduces the output significantly. Solar cells with a misalignment or which are partially in the shadow deliver less power output and these cells, with a bad performance, determine the output of the whole system. A dual-axe tracked array of solar cells can achieve an extra energy output of 40-50% compared to a fixed roof array that is tilted ideally for the latitude. For example, according to the 2010 report of Adrian Catarius and Mario Christiner, "Azimuth-Altitude Dual Axis Solar Tracker", "increases of power output can be achieved up to 43.87% for the two axes, 37.53% for the east–west, 34.43% for the vertical and 15.69% for the north–south tracking, as compared with the fixed surface inclined 32 degree to the south in Amman". [9] [10] [11]

3 TENSEGRITY

The word ‘tensegrity’, invented by Buckmister Fuller, is a combination of tension and integrity.[12] [13] The first-known three-dimensional tensegrity system is the one by Ioganson in 1920. He made a stable structure of three bars and nine strings. Because the bars did not contact each other it is a so-called first-class tensegrity system. Snelson [14] developed the tensegrity in 1948 as a new structural typology for lightweight space structures. As first-class tensegrity structures are difficult to install and calculate they have not been used very often as structural elements. Snelson made many structures as art objects, for instance the 1948 “free ride home” sculpture in New York and the needle tower in the Netherlands.[14] Tensegrity or tensegrity-like structures have been used in architecture for circular roofs. The first dome was designed by Fuller and is called after him. The domes have a triangle deviation of tensile strings and vertical bars within a circular compression ring. Geiger improved Fuller’s design by changing the triangular grid into a rectangular grid.[15] In the Geiger dome loads are carried from a central tension ring through a series of radial ring cables, tension hoops and intermediate diagonals.

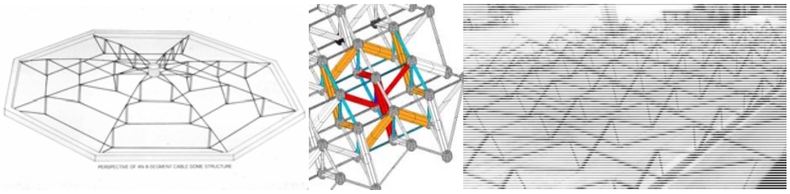


Fig. 1, 2, 3. Geiger dome, Double-layered grid by Snelson and by Motro 14 16 17

In 1960, Snelson designed a tensegrity structure with a tension and compression form similar to woven fabric [14]. Between 1998 and 2000 Motro et al. made this experimental double-layered grid of about 80 square meters with a weight of 12 kg per square meter. Their challenge was to prove that this structure can be built as easy as a regular space frame (see Fig. 3). By varying the length of de strings or rods Geiger domes or other tensegrity structures can be made kinetic, like the movable mast created by Frei Otto in 1976 [18]

4 DEVELOPING TENSEGRITY SYSTEMS

The roof of the Geiger dome is covered with membranes. The membranes are not meant to influence the tensegrity structure of the dome although this might be possible. Within a tensegrity structure it is possible to replace elements or to combine the tensegrity system with an:

(i) inflatable membrane;
(ii) mechanically pre-stress membrane; and
(iii)doubly curved surface (shell).

The first option (i) is de combination of an inflatable with a tensegrity. This combination can be divided into three types:

(a) an inflatable membrane with an air-supported outer surface;
(b) an inflatable membrane supports bars against buckling; and
(c) an inflatable substitutes the bars.

In the first type (a) the bars are replaced by the overpressure in the inflatable like in air mattresses, for instance a distance fabric (Fig. 4). If the strings form a 3D space structure such as in the inflatable cloud (Fig. 5) by Pronk, Lindner and students, the air mattress will be much stiffer. In the second type (b) the bars are supported by the surface of the inflated membrane against buckling. This typology is applied for the first time for a military bridge in 1965.[19] In 2004, Pedretti [20] called the structure "tensairity" and improved the structure by replacing the surface of the bridge by a bar within a seam of the membrane. Luchsinger [20] researched the working of this typology in depth. In the third type (c) the bars are replaced by inflatables. Koops studied in a Master thesis at the TU/e the replacement of bars by inflatables of a Geiger dome.[21] Pronk and Luchsinger researched the replacement of bars by inflatables of a tensairity.[20] [22]

Fig. 4. distance fabric Fig 5. Inflatable cloud

The second option (ii) is the combination of a tensegrity with a mechanically pre-stressed membrane. The replacement of strings by membranes was used for the first time in the rigid zeppelins by F. Zeppelin. The main rings of the zeppelin (Fig. 6) have been braced with strings against buckling in the radial direction. In the axonal direction the zeppelin structure is not braced with strings (Fig. 7) but covered with a membrane. As the bars are too slender and will buckle, the membrane must have fulfilled the bracing in the surface of the zeppelin similar to the structural support of the bars in the membrane surface of a tensairity.

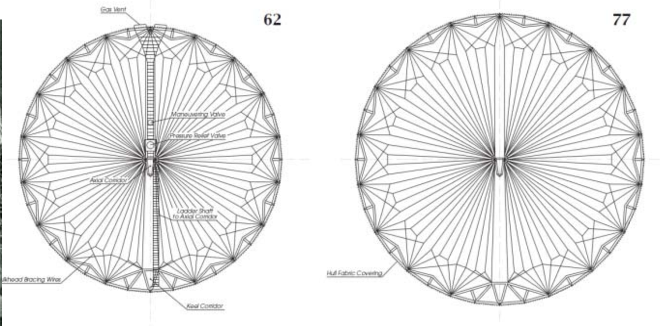


Fig. 6. Rings of Zeppelin 23 Fig. 7. Covering structure of Zeppelin with fabric 23

Maritza [24] researched the replacement of all the strings of a first-class tensegrity by membranes as shown in the models in Fig 8. She also searched for applications of this typology by designing and engineering a tensegrity dome structure.

The third option (iii) is to replace a bar and some strings by a hyperbolic shell surface (Fig. 8). The cable net with red borderlines and bar (red arrow) (Fig. 9) can be replaced by a doubly curved surface (Fig. 10). Students of TU/e researched the application of this typology by designing a second-skin façade for the rehabilitation of buildings.

Fig. 8. Tensegrity with membrane

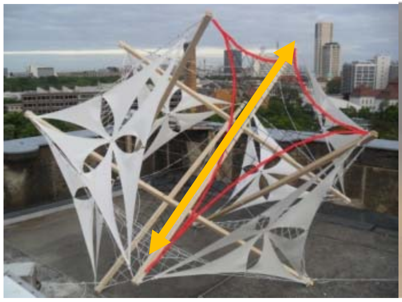


Fig. 9. Tensegrity with membrane in Berlin Fig. 10. Tensegrity with doubly curved glass for second-skin facade

5 KINETIC GEIGER DOMES

Kinetic deformation can be used to create a sun-tracking roof surface based on the Geiger dome typology. By using a combination of flexible and rigid components it is possible to transform the overall shape of the dome, so that, for example, the optimal sunlight radiation of the solar cells can be acquired (see Fig. 11).

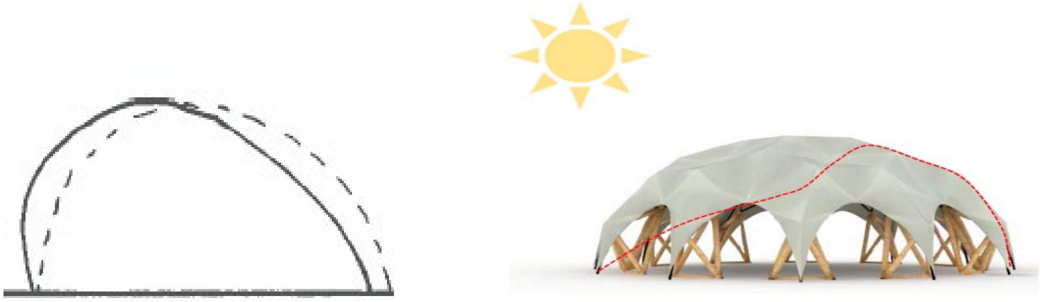


Fig. 11. Dome tracking a large part to the sun

In Fig. 11 the section of a regular Geiger dome is given. De bars (c) are vertical and the other parts are strings. The strings in (d) will form a regular hoop. The membrane surface is not structural and placed at the outside over the strings in (a). By changing the length of the strings it is possible to make different configurations as shown in the pictures above. It is also possible to vary the length of the bars. In this way Geiger domes or other tensegrity structures, like the movable mast created by Frei Otto in 1976,18 can be made kinetic. This mechanism is used to deform a dome based on the Geiger dome typology. The way a Geiger dome can be made kinetic can be achieved by (1) changing length of the bars or by (2) changing the length of the strings. The change of length can result in a sliding (a) or hinging (b) movement. The combination of those parameters results in four ways to make a Geiger dome kinetic:

(1a) changing length of the bars resulting in a sliding movement of bars and strings;

(1b) changing length of the bars resulting in a hinging movement of bars and strings;

(2a) changing length of the strings resulting in a sliding movement of bars and strings; and

(2b) changing length of the strings resulting in a hinging movement of bars and strings.

Option two is generally harder to achieve and more expensive therefore we only researched option (1a) en (1b) changing the length of the strings. For both options we have a designed a structure with sliding elements (1a) and with hinging elements (1b). This paper is limited to those two options. We did not research the turning of the roof surface around a vertical axis.

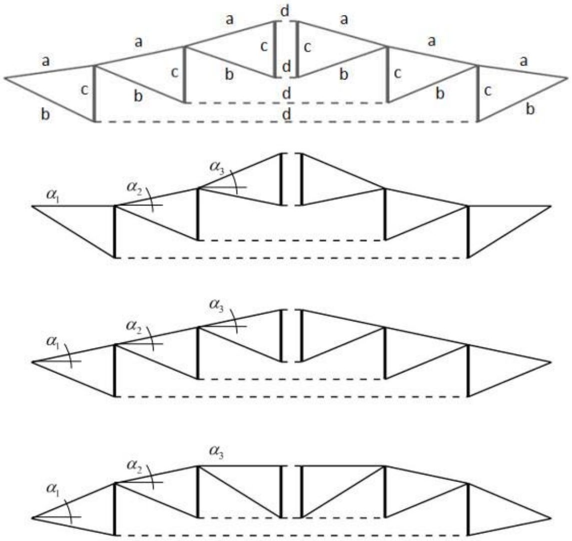


Fig. 12. Geigerdome in different configurations [21]

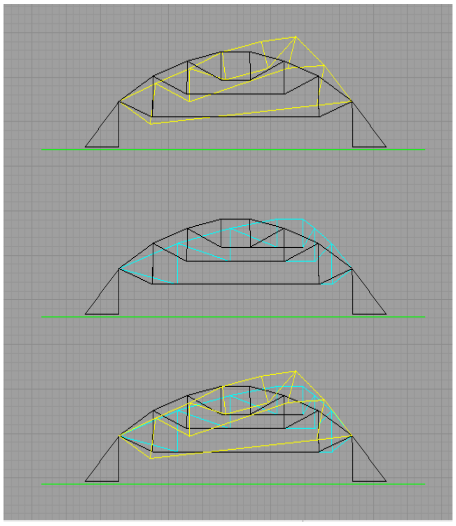


Fig. 13. Deformations of Geiger dome by hinging and sliding

In the figure above a regular Geiger dome is deformed by hinging (yellow) and sliding (blue). In the third picture both options are compared. The cantilevering angle is specified by the ratio between the length of the bars (H) and the distance between the rings (L). The higher the ratio between H/L the steeper the surface can be. The maximum angle of the roof surface is the tangent of H/L minus the sag of that ring.

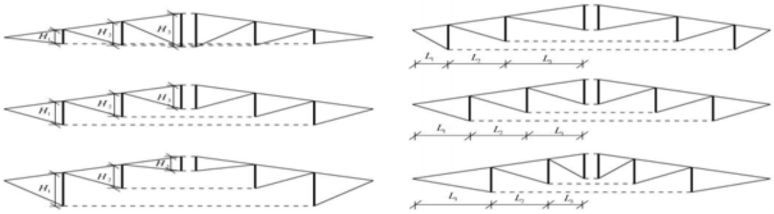
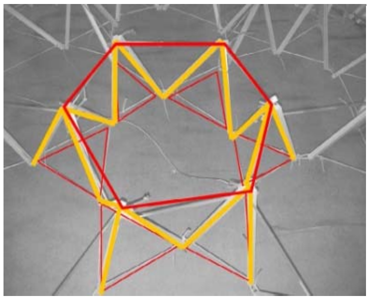


Fig. 14. Length of the bars (H), distance between the rings (L).[21]

With hinging it is possible to reach a higher point as the center of a regular dome. With sliding the center is only shifted and therefore hinging can give a stronger cantilever with the same ratio between H and L. But sliding might give a bigger surface turned to the preferred side. Regular Geiger domes are designed as lightweight structures, therefore striking elements like the compression bars are designed as slender as possible with a low H/L ratio and therefore a slender curvature with limited angle of the roof surface. In our case we need a maximum roof surface angle and therefore a high H/L ratio.

5.1 Kinetic tensegrity dome by means of hinging

The top and bottom net of a regular Geiger dome consists of concentric quadrangular net connected with straight bars. To introduce the forces to achieve a kinetic frame we have connected the upper and lower net with tetrahedrons. In the so-called "hex-tri-hex" configuration the upper net consists of hexagons and the lower net consists of a combination of triangles around a hexagon (Fig. 14).



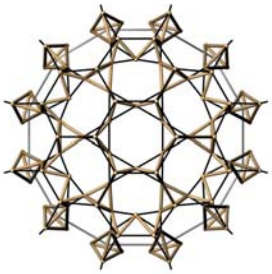


Fig. 15. Basic element of hex-tri-hex configuration Fig. 16. Top view of the kinetic tensegrity dome

The hex-tri-hex configuration was chosen because the upper hexagon grid is able to adapt deformations easily, the configuration of the lower grid is more stable and the connection between the layers with tetrahedrons is completely stable. The vertices of the tetrahedron are connected by hinges. The ground surface of the tetrahedrons of the first and third ring is made by strings, the one of the second ring by bars. In this configuration pulling or releasing the strings will make the tetrahedrons hinging. The circular strings in the lower net will provide stability. To realize the second tension ring in a regular way we had to deform the grid slightly. We proved the working of this configuration by making a physical model with sticks and elastics.

5.2 Kinetic tensegrity dome by means of sliding

For the sliding of a Geiger dome we did not have to change the morphology of the structure. As long as the stings are tensioned the structure will adapt the changes in length. To prove the sliding option we made some physical models with paper rings, sticks, strings and elastics. The models worked surprisingly well and easy. The distance between the rings is equal. While sliding the ratio of the distance between the rings is also equal (see Fig. 17).

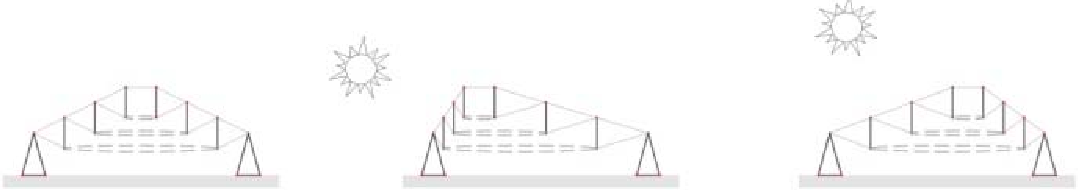
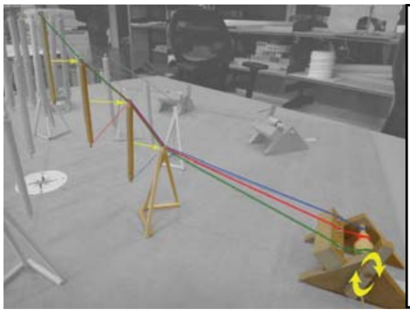


Fig. 17. Concept of sliding dome for low and high sun top view of kinetic tensegrity dome

Therefore the rings in the middle have a bigger movement as the outer rings. Within this context the ratio between the movement of the rings is equal to the mould of sliding rings. For example, with three rings the inner ring moves three times more as the outer ring. This is solved by varying the thickness of the spills (see Fig. 18).



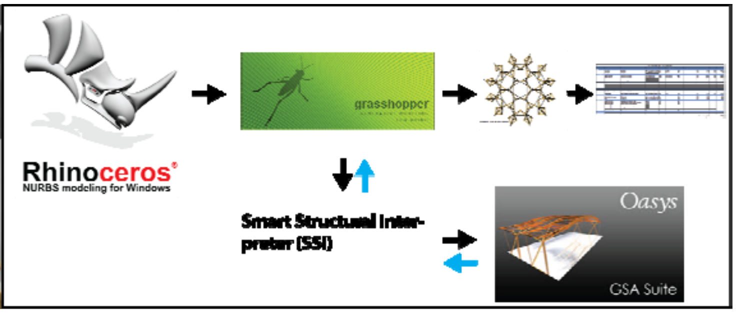


Fig. 18. Movement of the radial tension cables to achieve sliding Fig. 19. Collaboration between the programs [25] [26 27 28]

5.3 Digital Geiger dome

For this project we used several digital programs as a supportive tool to generate geometrical and structural properties and to simulate the dynamic behavior of the dome.We used Rhinoceros as the main program. Within Rhinoceros we used a plugin called Grasshopper, which makes it possible to program visually. Within Grasshopper we used a plugin ISS [27] to export the data to GSA. GSA is used for the FEM-analysis.28 The main focus in this research project was to produce a physical model. Structural analysis is used to require the structural properties of the elements.

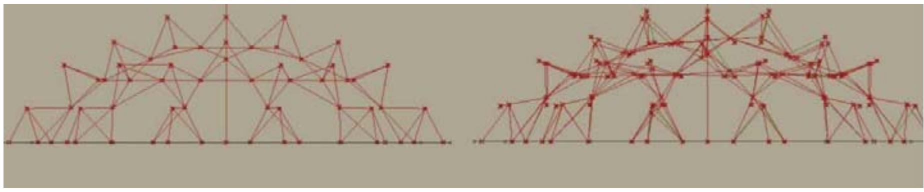
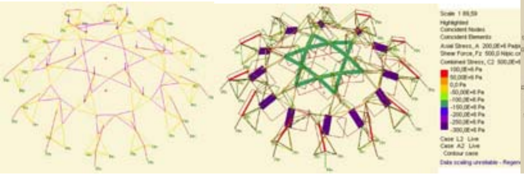


Fig. 20. Parametric model Rhinoceros-Grasshopper Fig. 21.Geiger dome in Rhinoceros environment

Rhinoceros and Grasshopper can be used to generate parametric models. In this project, we used Grasshopper to generate the structure and simulate the kinetic Geiger dome. The geometry of the Geiger dome is exported from grasshopper to GSA with a plugin called SSI. The data from SSI is used in GSA to perform a structural analysis (FEM-analysis).29 GSA allows non-linear and buckling analysis.28 The Loads used in GSA for the dome are according the Dutch Eurocode.30 The results of GSA were used to relocate the nodes and the members of the Geiger dome in Grasshopper (equilibrium based). The maximum displacement of the nodes were up to 15 cm.



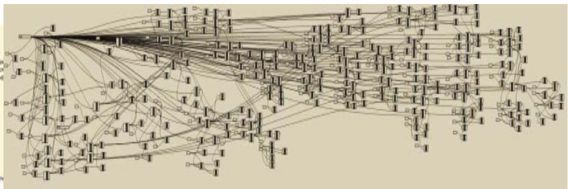
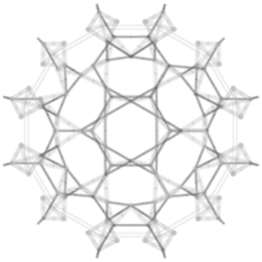


Fig 22. GSA output Fig. 23. Grasshopper script

With Grasshopper we made a script to generate the physical properties of the elements of the dome, like the coordinates of the nodes, the length of the members between the nodes and the amount of nodes and members.



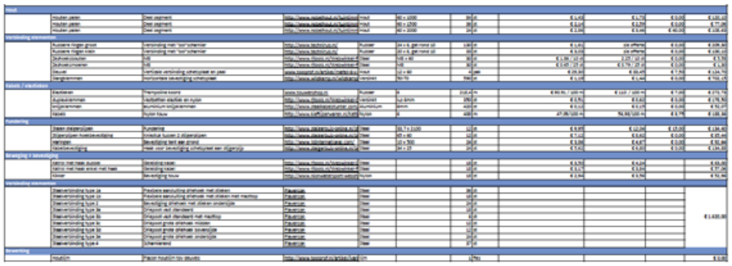


Fig. 24 Grasshopper output Fig. 25 Output Grasshopper to Excel

These physical properties are exported to an excel file, and used to order materials and for creating the physical model.

6 BUILDING THE KINETIC GEIGER DOME

The building of the first prototype was conducted in 10 weeks, after modeling the kinetic geometry in Rhino and building models scale 1:20. In the dome we developed the rigid components which were made from a combination of wood and steel (see Fig. 26). The flexible wires were adjusted with hand-powered pulleys.

Fig. 26 Top view of the dome, model and detail

After producing the parts the prototype was mounted. Due to a poor mounting plan and a relatively large weight the joints deformed. The dome missed a balance and its full erection was halted. Next steps where to reduce the weight further, make a better mounting plan and to keep the move-ability of the dome under control. Learning from the first prototype the assignment for the students for the second prototype was to design and build a kinetic Geiger dome. By changing the length of the diagonal cables while keeping the circular cables and struts the same length this kinetic Geiger dome can create a large and relatively flat surface which can be directed to the sun. Therefore the change of the shape of this prototype will enhance the output of the solar cells or can deliver the same output with less square meters of solar cells. The Geiger dome is lighter as the first prototype and as the tension rings and struts are kept as they are the geometry is stable while being kinetic. The diagonal tension cables are either pulled or slacked, while under tension. The prototype showed that the movement is realized as the model scale 1:10 predicted. The solar cells will be integrated in a membrane that can slide over the movable geometry. The angle of the cells can be between 27 and 65 degrees, which is sufficient for Portugal. The prototype of the dome was scaled down because of the available poles from the first dome prototype, a maximum span of 4 meters was possible. Next step in the research is to increase that to 10 meters. A research was done in 6 different ways to slide the cables through the struts. A production manual was made how to build the dome.

Fig. 27. (a + b) movement of the dome, (c + d + e) details of the dome and the hand-powered pulleys.

7 CONCLUSIONS

The objective was to make a kinetic geometry in order to let the solar cells follow the path of the sun. That objective was met although the solar cells where simulated and the spans of the prototypes are limited. The final kinetic Geiger dome has a span of approximately 4 meters. Next step is to make a larger span, and to research how to use electric motors instead of hand-powered pulleys to be able to control the movement better and keep the pre-tension in the geometry. Point of attention is that the forces upon the motors will increase enormously when the dome is scaled up. With a larger span a further reduction of the dead load is necessary, other materials for the struts have to be considered. The length of the cables should be exactly correct or adjustable. The sliding of a skin with solar cells needs a better design idea. And last but not least the anchoring to the ground must be redefined.

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